"Development of Lightweight Prime Power Source Components for Pulsed Applications"

by

T. R. Childers, C. N. Coyne, G. J. Sullivan,
J. H. Ferrick, and L. I. Amstutz

of the

Belvoir Research, Development and Engineering Center (BRDEC)
Electric Machinery Team (STRBE-FGE)
Ft. Belvoir, VA. 22060-5606.

ABSTRACT

This paper discusses some state-of-the-art approaches and options for development of very lightweight prime power source components and sub-systems suitable for pulsed applications. Prime power refers to components which convert available energy (typically kerosene based fuel) into useful electrical power for pulsed systems (high power radars (HPRs), high power microwaves (HPM), lasers or kinetic energy weapons (KEWs)).

A discussion of two projects undertaken by BRDEC will illustrate some of the approaches available to achieve high power density prime power systems. These projects include:

a. The design effort for a 1 MW power source for a conceptual airborne application. This effort is discussed in Part 1.

b. The Tech Base high speed, high power density Bendix alternator effort. This is discussed in Part 2.

INTRODUCTION

Concepts and ideas abound using pulse compression techniques to power tactical, mobile pulsed electromagnetic (EM) weapons and countermeasure systems. Tactical mobility is needed for "shoot and scoot" battlefield scenarios. However, successful development of mobile pulsed systems is often hindered by the size/weight of the prime power source. A typical prime power source consists of some kind of engine to convert fuel to mechanical energy, an alternator to create electrical power, and first stage conditioning for power driving the pulsed system. Typically, pulsed systems require d.c. power, either high voltage (HV) or high current. These systems often require large amounts of average power for effective operation.

This paper examines current requirements for mobile, tactical prime power systems: small size, low weight, high reliability, and logistic supportability.

PART 1: 1 MW PRIME POWER SOURCE

ENGINE DESIGN (AIRBORNE APPLICATION)

The pulsed system generally is integrated with a mobile platform (aircraft, land vehicle, or ship). Tactical aircraft usually provide the greatest size/weight constraints, while ships provide the least. Sometimes the existing platform engine can be used; if not, a separate engine must be integrated. Turbine engines provide high power density while reciprocating engines are less power dense. Rotary (Wankel) engines operating on kerosene based fuels may become commercially available. These engines would provide design and cost flexibility between turbine and reciprocating engines.

The 1 MW power source design effort illustrates a typical system requiring a turbine. The prime power system is required to reside in a Mach 2 missile. The small space available (30" diameter, 6' long) coupled with high power requirements calls for a lightweight turbine. A diesel fueled ram-air compression turbine engine was chosen to make use of the existing Mach 2 airflow. System considerations required minimizing air scoop drag on the missile. Drag was partially compensated by using the engine exhaust for thrust. The short operating time (4 min) required 5 gallons of fuel for a nominal 1700 hp output.

Engine design parameters: 30,000 r/min, 1.25 MW, 200 lbs, 22" long, 18" diameter, 7 lbs/sec mass flow rate, 1,700 degree F turbine inlet temperature. [1]

ALTERNATOR CONSIDERATIONS

The choice of alternator for this conceptual application is dictated by system constraints and the engine to be used. High speed operation usually translates to high power density alternators. A reciprocating engine typically operates at 6,000 r/min or less. A turbine engine directly driving a high speed alternator provides a system with the best power density. However, development of custom, high speed alternators can be costly. Commercial aircraft alternators are available up to 24,000 r/min, but usually with powers no higher than 200 kW. Some 250-550 kW 400 Hz air-cooled machines are designed and built with weights in the 500-600 # range. High speed alternators can be used with reciprocating engines at the expense of gearbox weight, which may offset any gains.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1991**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Development of Lightweight Prime Power Source Components for Pulsed Applications**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Belvoir Research, Development and Engineering Center (BRDEC) Electric Machinery Team (STRBE-FGE) Ft. Belvoir, VA. 22060-5606**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

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15. SUBJECT TERMS
4

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**3**	

For the 1 MW power source, a custom high speed, high frequency (2 kHz) alternator was chosen to meet size/weight constraints. The alternator is directly coupled to the engine, thus operating at 30,000 r/min. The alternator is a permanent magnet axial-gap (PMAG) design utilizing a composite wrapped rotor to contain mechanical stresses generated at operating speed. Permanent magnets simplify rotor design at the expense of direct control of the rotor fields (output voltage). For this application, however, small variations in generator voltage and frequency are acceptable. A small active cooling system was designed for the alternator to handle some of the excess heat. Coolant is pumped through hollow stator conductors to absorb conductor losses; maintaining a closed primary cooling loop. Heat is exchanged with a vaporizing coolant which is dumped overboard when pressure relief settings are exceeded. Due to the short operating time, the alternator thermal inertia could absorb a large portion of excess heat.

PMAG alternator design parameters: 30,000 r/min, 1 MW, 270 lbs, 16" long, 22" diameter, 3-phase, 2 kHz, 1,950 V L-N and WYE output. [2] [3]

FIRST STAGE POWER CONDITIONING

Typically, first stage power conditioning is a rectifier to convert a.c. from the alternator to d.c. This d.c. power usually feeds energy storage/pulse compression circuits. Often a transformer is used before rectification to obtain the desired d.c. voltage. Pulsed systems like KEWs usually require lower voltages and high currents; the reverse is true for HPRs and HPM systems.

High frequency operation means smaller transformers. Thus high frequency alternators are not only lightweight themselves, they allow for smaller, lighter transformer/rectifier (T/R) units. The core is usually one of the heaviest pieces in a T/R unit, and it's size decreases with increasing frequency.

The T/R design for the 1 MW power source is straightforward using a 3-phase DELTA-WYE transformer and full wave bridge rectification. State-of-the-art HV rectifiers and high frequency operation combine to create high power density. The T/R is immersed in dielectric fluid which prevents voltage breakdown and acts as a passive thermal reservoir during operation.

T/R design parameters: 220 lbs wet, 7 cu.ft., 3-phase DELTA-WYE, 100 kV peak output and 150 kV peak inverse voltage. [4]

SYSTEM INTEGRATION

This section provides an overview of system integration for the 1 MW power source components and power source integration with the pulsed load. This will illustrate integration issues common to many pulsed systems.

An optimum engine/alternator design speed would minimize weight and prevent operation near critical speeds. Alternator design weight decreased with speed as did the engine design weight, analysis showed 30,000 r/min to be optimum.

The 1 MW power source is designed to charge an energy storage capacitor, which is the first stage of pulse conditioning. The capacitor is completely discharged within a few μs at the end of a 50 ms charge cycle. After discharging, the capacitor initially behaves much like a short circuit. The system was modeled, and alternator-T/R reactance designed, to prevent excessive currents during the early portion of the charge cycle (reactance acts to limit surge currents). Conversely, the design reactance was limited to assure full charging to the desired 100 kV peak at the end of the charge cycle. See Fig 1. for an illustration of the 1 MW power source. See Fig 2. for a graph of the 1 MW power source charging waveforms.

Analysis indicated that peak power flow into the capacitor occurs about midway through the charge cycle. The varying power flow gives rise to cyclic mechanical and electric stresses. The components were designed to withstand these stresses. [5]

Handling excess heat is an everpresent issue in prime power source design. The best approach is to use efficient components. Alternators and T/Rs are inherently efficient, operating in the 93% and 98% efficiency range respectively. However, with the high average power required, even these efficiencies give rise to significant excess heat. The relatively short (4 min) operating time allowed the thermal capacitance of the components to absorb most excess heat. Longer operating times would necessitate the use of active cooling.

1 MW POWER SOURCE DESIGN EFFORT STATUS

Preliminary designs for the ram-air and diesel fueled engine and PMAG alternator are complete; T/R preliminary and detailed designs are complete. Final power source design parameters are: 1 MW rated, 690 # total weight, 70" long and roughly 15 ft^3 displaced (28 ft^3 occluded) volume. The effort is now discontinued.

MODIFICATIONS FOR A GROUND BASED, LONG DUTY SYSTEM

The 1 MW power source can be adapted for mobile, ground based, longer duty applications. The engine discussed could be modified with the addition of a compressor stage, or an appropriate engine with an integral compressor could be chosen (an advanced development version with similar operating speed weighs about 250 #). An active cooling system with a single common coolant could be developed for long term operation of the alternator and T/R.

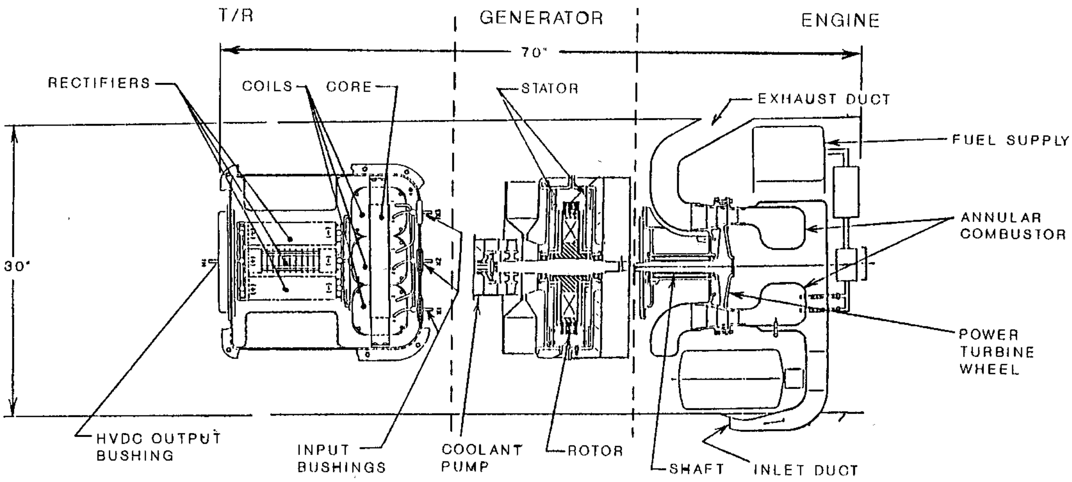

Fig 1. Detailed Illustration,

1 MW Power Source Components.

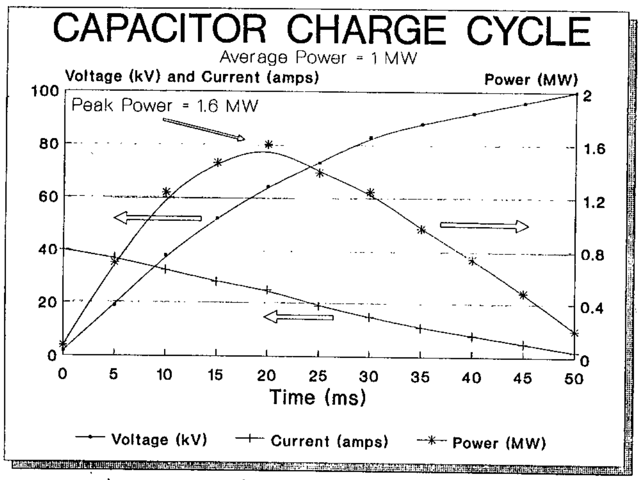

Fig 2. Capacitor Charging Waveforms.

PART 2: BENDIX HIGH SPEED ALTERNATOR

This Tech Base effort led to the design and fabrication of 3 prototype oil-cooled, 3-phase synchronous alternators with the following parameters: 3 MW, 850 lbs, 30" long, 14" diameter, and a 10,000-15,000 r/min speed range (700-1,000 Hz). A prototype alternator was tested to 1.7 MW using BRDEC's in-house test facilities. These facilities include a turbine powered test stand for alternator tests up to 3 MW and beyond. Design deficiencies are corrected, final alternator design modifications are completed, and a prototype is ready for full range power tests pending authorization.

This alternator represents the state-of-the-art in power density for synchronous machines. A sealed housing and oil cooling allows the alternator to be used in contaminated or dirty environments. An oil-cooled T/R unit, fabricated by Thermal Technology Inc., can provide 3 MW of d.c. power at 10 kV when powered by the alternator. The alternator and T/R use a common dielectric-lubricant-coolant.

System components include the Textron-Lycoming T-55 turbine, Bendix alternator, Thermal Technology T/R unit, cooling, and miscellaneous components. System weight is roughly 1,100 kg, yielding a power density of 2 kW/kg.

CONCLUSIONS

Well developed designs and experimental components exist for fabrication of very lightweight (1-3 kW/kg) prime power systems suitable for mobile, tactical pulsed applications. Advances in engine and alternator design and materials technology will allow for continued increases in power density for prime power systems.

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